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HYPER EXTREMELY RED OBJECTS IN THE SUBARU DEEP FIELD: EVIDENCE FOR PRIMORDIAL ELLIPTICAL GALAXIES IN THE DUSTY STARBURST PHASE*

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ABSTRACT

We report observational analyses and theoretical interpretations of unusually red galaxies in the Subaru Deep Field (SDF). A careful analysis of the SDF data revealed a population with unusually red near-infrared (NIR) colors of $J-K \gtrsim$ 3–4, with higher confidence than the previous SDF result. Their surface number density drastically increases at $K \gtrsim 22$ and becomes roughly the same with that of dusty starburst galaxies detected by submillimeter observations in recent years. These colors are even redder than the known population of the extremely red objects (EROs), and too red to explain by passively evolving elliptical galaxies which are the largest population of EROs. Hence these hyper extremely red objects (HEROs) should be considered as a distinct population from EROs. We discuss several possible interpretations of these enigmatic objects, and we show that these red NIR colors, K-band and sub-mm flux, and surface number density are quantitatively best explained by primordial elliptical galaxies reddened by dust, still in the starburst phase of their formation at $z \sim 3$.

Subject headings: cosmology: observations — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation

*Based on the data corrected at the Subaru telescope, which is operated by the National Astronomical Observatory of Japan.

1. INTRODUCTION

The reddest populations of galaxies are of great interest in the study of galaxy formation and evolution, since they are showing one of the most extreme aspects in the history of galaxies and structure formation. A population called extremely red objects (EROs) is already established, showing very red colors between the optical and NIR bands, e.g., $R-K \gtrsim$ 5–6 (e.g., Elston, Rieke & Rieke 1988; McCarthy, Perrson, & West 1992; Hu & Ridgway 1994; Thompson et al. 1999; Yan et al. 2000; Scodeggio & Silva 2000; Daddi et al. 2000a,b). Daddi et al. (2000a) argued that a large part of this population consists of passively evolving elliptical galaxies at $z \sim$ 1–2, based on the strong clustering of field EROs. A smaller fraction of EROs seems to be ultra-luminous infrared galaxies (ULIRGs) with $L_{\rm IR} > 10^{12} L_\odot$ under dusty starbursts, some of which are also observed as submillimeter sources (Cimatti et al. 1998; Dey et al. 1999; Smail et al. 1999; Gear et al. 2000).

The process by which elliptical galaxies form is an important issue in galaxy formation and cosmology. One popular scenario is that they are formed with an intense initial starburst, followed by passive evolution without star formation to the present (Larson 1974; Arimoto & Yoshii 1987). Passively evolving elliptical galaxies are expected to show very red optical-NIR colors at $z \sim$ 1–2. The colors and number density of EROs are well consistent with this picture of elliptical galaxy formation (Daddi, Cimatti, & Renzini 2000b). On the other hand, the starburst phase at the formation of elliptical galaxies has not yet been discovered. If the starburst phase is not dusty their redshifted UV radiation should have easily been detected by the past optical surveys (e.g., Totani, Sato, & Yoshii 1997), and hence it has been suggested that elliptical galaxies have formed with dusty starbursts or hierarchical merging of smaller objects at relatively low redshifts (e.g., Zepf 1997).

Therefore search for dusty starbursts at high redshift is very important to verify the above picture of elliptical galaxy formation. In recent years, there has been dramatic progress in submillimeter observations, and it has revealed redshifted dust emission from high-z starbursts (Hughes et al. 1998; Barger et al. 1998). Although their inferred star formation rates ($\gg 100 M_\odot$/yr) are consistent with those expected in the "monolithic-like" collapse scenarios, the evidence for connection between these SCUBA sources and elliptical galaxies is rather weak based on the submillimeter observations alone, due to the lack of a quantitative connection with present-day elliptical galaxies. In fact, optical observations have failed to identify the counterparts for most of the SCUBA sources (Dunlop 2001).

Here we report a discovery of unusual objects in the Subaru Deep Field (SDF, Maihara et al. 2001), which are even redder than EROs and too red to explain by passively evolving elliptical galaxies at $z \lesssim 2$. Therefore these hyper extremely red objects (HEROs) should be considered as a distinct population from previously known EROs. The SDF is one of the deepest images of the universe yet obtained in the NIR bands. The J and K band images have been taken for a $2' \times 2'$ field, with the limiting magnitudes of $J = 25.1$ and $K = 23.5$ at 5σ level. SDF found

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385 and 350 galaxies down to these magnitudes, respectively. The first-pass analysis of this image revealed four very red objects in the $J-K$ color. (The reddest color is $J-K = 4.12 \pm 1.04$ for an object with $K = 22.31 \pm 0.14$, see Maihara et al. 2001.) However, because of possible observational uncertainties in the photometry, it was not strongly claimed that there really exist objects with $J-K > 4$. What we report here is a new, more careful analysis, to investigate how many objects with such red colors actually exist in the SDF. Indeed, we obtained stronger evidence for the existence of such unusually red NIR color objects with $J-K > 3$–4. We will then discuss several possible interpretations of these HEROs, and argue that these objects are likely to be primordial elliptical galaxies in the dusty starburst phase.

2. HEROS IN SDF

We estimated how many objects really exist in the SDF, with colors redder than a given $J-K$ color. The results are shown by a number fraction of such red objects as a function of K magnitudes in Fig. 1, down to magnitudes fainter than the previously reported four objects. We should be very careful in this analysis, because the J band flux of red objects is very faint by definition, although they may be detected easily in the K-band. We took the analysis procedure as follows to carefully take into account the effects of photometric uncertainty. First, SDF objects are distributed onto two-dimensional bins in K magnitude and $J-K$ color. Expected counts of spurious objects are then subtracted from each bin, based on their estimated color distribution from the reference frame (Maihara et al. 2001). (In fact, since the 5σ detection limit of the SDF is $K = 23.5$, contamination of spurious objects is not significant at $K < 23.5$.) To estimate the effect of photometric uncertainties, we performed Monte Carlo simulations in which the magnitudes and colors are perturbed according to their estimated error distributions; the resulting dispersion of the counts in each bin is added to the error arising from spurious object subtraction. Here, an asymmetric distribution of photon counts is used for the photometric error distribution, also taking into account the galaxy count slope (see Maihara et al. 2001 for details). This final error estimate is then shown in Fig. 1.

The data show that there exists a very red population with $(J-K) > 3$–4, having a number fraction of 1–10% at $K \gtrsim 22$, about one order of magnitude higher than that at brighter magnitudes of $K \lesssim 20$ (Scodeggio & Silva 2000). Dickinson et al. (2000) has reported an unusual object with $K = 22.0$ and having a very red color ($J-K > 4.6$) in the Hubble Deep Field (HDF). This object is most likely a brighter example of the population we have found here. Saracco et al. (2001) found a fraction (~ 5%) of sources with color redder than $J-K_s = 2.3$ at magnitudes $K_s > 20$, which is also consistent with our result. The numbers of real objects estimated for the reddest galaxies in the SDF with $(J-K) > 4$ are $1.0 \pm 0.41(2.4\sigma)$ and $3.81 \pm 1.44(2.6\sigma)$ in $K = 22.0$–22.5 and 23.0–23.5, respectively.

Even EROs do not show unusually red colors within the NIR bands; typical EROs have colors of $J-K \sim 2$ (Scodeggio & Silva 2000). These colors should also be compared with typical theoretical predictions for passively evolving elliptical galaxies. Here we use a typical model of elliptical galaxies ($M_B = -20$) without dust obscuration (Kodama & Arimoto 1997). A low-density flat universe with $(h, \Omega_0, \Omega_\Lambda)$ = (0.7, 0.2, 0.8) is assumed here and throughout this letter. This model predicts that the $J-K$ color should be bluer than 2.5 at $z \lesssim 2$ for any formation redshift (dotted lines in Fig. 2). This is well consistent with Fig. 1 of Scodeggio & Silva (2000) using a different evolution model of Bruzual & Charlot (1993).

3. INTERPRETATIONS OF HEROS

Passively evolving ellipticals at even higher redshift (formation redshift $z_F \gg 3$) may have redder colors, comparable with HEROs, but still the maximum color does not exceed $J-K > 4$ without reddening by dust (dotted lines in Fig. 2). Zepf (1997) argued that the absence of extremely red objects with $V_{606}-K > 7$ in HDF rules out models in which typicall elliptical galaxies are fully assembled and have formed all of their stars at $z \gtrsim 5$. Such a large z_F is also disfavored from the constraint that major episodes of star formation should have taken place at $z \lesssim 3$, as inferred from the observed colors of elliptical galaxies at $z \sim 1$ (Franceschini et al. 1998). Two possibilities then remain to account for the origin of objects with such red colors: (1) starburst galaxies obscured by dust, or (2) very high-z Lyman-break galaxies at $z \gtrsim 10$. The possibilities of any point sources such as quasars or very red stars in the Galaxy are rejected by the extended profiles of the HERO images. The exclusion of point sources in the SDF is secure down to $K \sim 23$ (Nakajima et al. 2000), and see Maihara et al. (2001) for images of the four brightest HEROs. We will then argue in the following that the scenario (1) provides the best explanation for presence of HEROs in the SDF data.

It is easy to show that elliptical galaxies at the formation stage are likely to be very dusty, with an optical depth more than 10 for UV radiation, based on the expected column density of dust (e.g., Totani & Yoshii 2000). This is in contrast to spiral disks, in which dust opacity does not become much higher than in present-day galaxies because of the modest star formation generally believed to have taken place (Totani & Kobayashi 1999). We show the model colors of a typical elliptical galaxy in the presence of dust obscuration in Fig. 2, according to the dust modeling used in Totani & Yoshii (2000). The dust opacity is assumed to be proportional to the gas column density and gas metallicity. A natural normalization factor for the dust opacity has been chosen to reproduce a typical mean extinction of $A_V \sim 0.2$ for our Galaxy. The Galactic extinction curve (e.g., Mathis, Mezger, & Panagia 1983) is used. It should be noted that we will mainly consider dusty galaxies at $z \sim 3$, corresponding to the restframe wavelength of $\lambda > 3000$ Å where the difference of extinction curves between the Galaxy, Magellanic Clouds, and starburst galaxies is almost negligible (e.g., Calzetti, Kinney, & Storchi-Bergmann 1994). In the model we assumed that the gas fraction exponentially decays as $f_g \propto \exp(-t/t_{\rm GW})$ after the time of galactic wind ($t_{\rm GW} = 0.3$Gyr here). The model prediction depends on the assumed spatial distributions of dust: screen or slab (the same distribution for stars and dust).

Figure 2 shows that a typical giant elliptical galaxy with screen-type dust shows a very red color of $(J-K) > 3.5$ at $K \gtrsim 21$, in good agreement with the properties of HEROs. The screen model is not unreasonable, because the galactic wind, expected to be driven by the strong starbursts of forming elliptical galaxies (Arimoto & Yoshii 1987), would also blow out the dust particles. It also seems that at least a fraction of dust has a screen-like distribution in observed starburst galaxies, as suggested by strong reddening that cannot be explained only by the slab-type dust model (Calzetti, Kinney, & Storchi-Bergmann 1994; Gordon, Calzetti, & Witt 1997). The $J-K$ colors of typical "template" dusty starburst galaxies, i.e., Arp 220 and the nucleus of M82, are also shown when they are placed at high redshifts. They are redder than passively evolving elliptical galaxies at fixed redshifts, and the color of M82 reaches $J-K \sim 3.5$ at $z \sim 2.5$.

Therefore primordial elliptical galaxies in the starburst phase, obscured by screen-like dust, are a promising candidate for the HEROs in the SDF. To test this hypothesis, we predict the expected surface number density of such objects based on the number density of the present-day elliptical galaxies determined by the local luminosity function (model curves in Fig. 1). The model calculation is the same as presented in Totani & Yoshii (2000). The total counts of all galaxy types of this model already fit well to the SDF counts (Totani et al. 2001a, b), and hence agreement in the number fraction simultaneously warrants the agreement in real counts. The model with $z_F = 3$, which is consistent with the redshift constraints of Zepf (1997) and Franceschini et al. (1998), agrees well with the observed number fraction of HEROs with $J-K \gtrsim$ 3–4 as a function of K magnitude, lending further support for the hypothesis that HEROs in the SDF are dusty primordial elliptical galaxies. The predictions with $z_F > 5$ overproduce HEROs beyond the upper limit at $K = 20$, while they are rather favored from the data with $J-K > 2.5$ and $K > 23$, possibly due to the contribution of relatively small, faint elliptical galaxies with large z_F. This may suggest that smaller elliptical galaxies have formed earlier than massive ones, as expected from hierarchical structure formation. To estimate the uncertainty concerning dust extinction, we repeated the calculation with different values of the normalization of dust optical depth. Changing this parameter by a factor of up to 4 does not significantly change the prediction, as shown in the figure.

If, on the other hand, HEROs are high-z Lyman-break galaxies, their redshift must be $z \gtrsim 10$ for the J band to correspond to the restframe wavelength of $\lesssim 1000$Å. The absolute UV luminosity inferred from $K \sim 22$ then implies a star formation rate of $\gtrsim 140 M_\odot$/yr, ignoring dust extinction (see Madau, Pozzetti, & Dickinson 1998 for conversion factors). It would be difficult to convert all baryonic gas within a time scale shorter than a typical dynamical time or duration of starburst, i.e., $\sim 10^8$yr, and hence a conservative lower bound for the baryonic mass of these systems is obtained as $M_B \gtrsim 10^{10} M_\odot$, or the total mass of $M \gtrsim 10^{11} M_\odot$ including dark matter. We should then examine how many such massive objects could have already formed at such high redshift, from the viewpoint of the standard theory of bottom-up structure formation induced by cold dark matter (CDM). We have calculated the surface density of objects with $M > 10^{11} M_\odot$ at $z > 10$ using the standard Press-Schechter formalism in the Λ-CDM universe with $\sigma_8 = 1$, presently favored by various cosmological observations, and found that it is about ~ 0.16 in the SDF. [See, e.g., Kitayama & Suto (1996) for the calculation method]. This is considerably smaller than the observed number of HEROs in the SDF (~ 10), in spite of the conservative lower mass limit. By contrast, the same estimate for objects with $M \sim 10^{12-13} M_\odot$ at $z \sim$ 3–5, expected typical values for dusty primordial elliptical galaxies, becomes about 30 in the SDF; this is then sufficient to explain the observed number of HEROs. It should also be noted that very high-z ($z > 5$) passively evolving elliptical galaxies are again disfavored as the origin of HEROs from this viewpoint.

4. POSSIBLE CONNECTION TO SUBMILLIMETER SOURCES

If HEROs are actually strong starbursts obscured by dust at $z \sim 3$, they are expected to be strong sources in the submillimeter bands as a result of their redshifted strong dust emission. SCUBA has revealed high-z starbursts with surface density of about 10^7 sr^{-1} down to $S_\nu \sim 1$ mJy in the 850μm band (Hughes et al. 1998; Barger et al. 1998). In the following we show that a considerable part of the SCUBA sources are likely to have the same origin with HEROs in the SDF, for which we have already shown a quantitative connection to the present-day elliptical galaxies.

First, the total galaxy counts (Maihara et al. 2001) down to $K \sim$ 22–23 is about 10^5 deg^{-2}. By using a fraction of about 3% of the HEROs in the SDF, the surface density of HEROs becomes $\sim 10^7$ sr^{-1}, in good agreement with the number density of SCUBA sources. Furthermore, we can predict the submm flux from HEROs, based on the model used here. We calculated the total luminosity of dust emission from the amount of stellar light absorbed by dust, and then obtained the expected mid- and far-infrared spectral energy distribution (SED) of dust emission by a model (Takeuchi et al. 2001) based on the empirical relation between total luminosity of dust emission and dust SED of local infrared galaxies (e.g., Soifer & Neugebauer 1991). The prediction for the observed flux and SED for several values of redshifts is shown in Fig. 3 for a typical giant elliptical galaxy. This figure shows that dust emission from HEROs at $z \sim 3$ can actually be detected in the 850μm band with the SCUBA sensitivity ($S_\nu \sim$ mJy, shown by a filled diamond at 850μm). The redshift of $z \sim 3$ inferred from our analysis and Franceschini et al. (1998) is also well consistent with the median of the redshift estimates for SCUBA sources (Dunlop 2001).

5. CONCLUSIONS

Based on the arguments presented above, we conclude that the best interpretation of the newly discovered HEROs is that we are now beginning to detect high-z dusty starbursts, whose number density, NIR colors and magnitudes, and SED from NIR to submillimeter bands are quantitatively consistent with the expectations of primordial elliptical galaxies forming at $z \sim 3$. An urgent task in the near future is to establish the link between HEROs and SCUBA sources by follow-up observations for each population. Further confirmation of our results would come in the more distant future by next generation instruments, such as SIRTF, ASTRO-F, Herschel Space Observatory, NGST, and ALMA (see Fig. 3 for their target sensitivities). These will provide further valuable information for the epoch of rapid and hidden star formation in the early universe.

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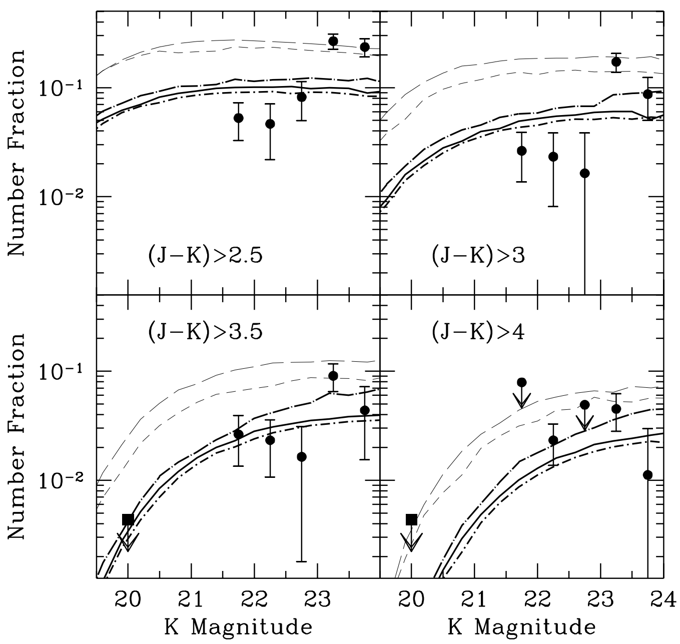

FIG. 1.— Number fraction of galaxies redder than several threshold $J-K$ colors (indicated in each panel), as a function of K magnitude. Filled circles are the data of the SDF. The error bars are 1σ, while the upper limits shown by arrows are at the 95% confidence level. The upper limit at $K = 20$ is from Scodeggio & Silva (2000, filled square). The solid line is the model prediction with the formation redshift $z_F = 3$ and our standard dust-extinction normalization. The short- and long-dot-dashed lines are the same as the solid line, but for the cases with dust-extinction normalization multiplied by factors of 2 and 1/2, respectively. The thin short- and long-dashed lines are the same as the solid line, but for $z_F = 5$ and 7, respectively.

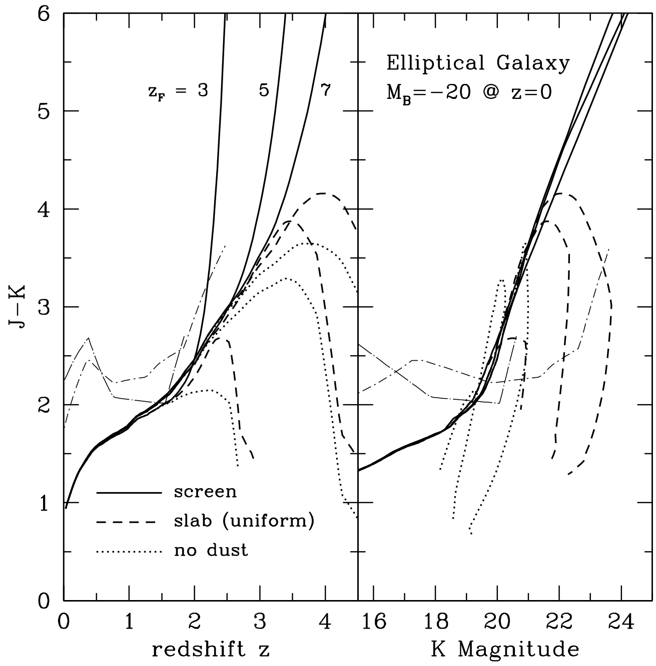

FIG. 2.— The $J-K$ color versus redshift and K magnitude relation for a standard model of elliptical galaxies with the present-day magnitude of $M_B = -20$, with different models of dust extinction: no dust (dotted), slab-type dust (dashed), and screen (solid line). Three curves are depicted for each of the three line markings, corresponding to different values of formation redshift, z_F = 3, 5, and 7, from left to right with increasing z_F. In addition, the colors and magnitudes of typical "template" starburst galaxies of Arp 220 (long-dot-dashed; photometric data from Sanders et al. 1988 and Carico et al. 1990) and the nuclear region of M82 (short-dot-dashed; photometric data from Johnson 1966 and Ichikawa et al. 1995).

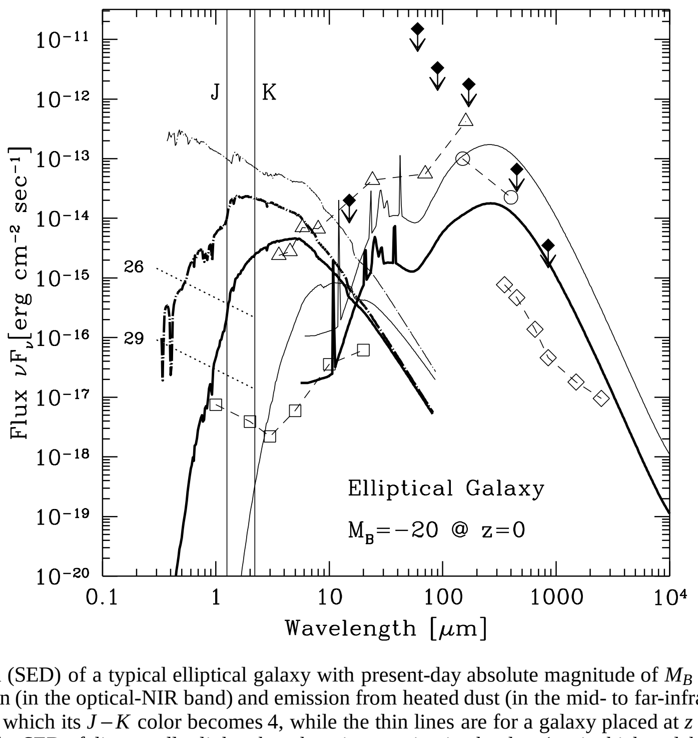

FIG. 3.— Spectral energy distribution (SED) of a typical elliptical galaxy with present-day absolute magnitude of $M_B = -20$ and $z_F = 3$. The two components of direct stellar light surviving absorption (in the optical-NIR band) and emission from heated dust (in the mid- to far-infrared band) are shown by solid lines. The thick lines are for a galaxy at $z = 2.3$, at which its $J-K$ color becomes 4, while the thin lines are for a galaxy placed at $z = 2.7$, corresponding to the epoch of the galactic wind. The dot-dashed lines are the SED of direct stellar light when there is no extinction by dust (again thick and thin lines for $z = 2.3$ and 2.7, respectively). Dotted lines in the optical and NIR wavelengths show the flux corresponding to the *AB* magnitudes of 26 and 29, showing the sensitivity limits of the SDF in the *K* band and HDF in optical bands, respectively ($K_{AB} = K + 1.85$). The wavelengths corresponding to *J* and *K* bands are indicated. Filled diamonds with lower arrows are the sensitivity limits which have been achieved by past instruments in infrared bands. The open symbols connected by dashed lines are the expected sensitivities of future experiments: the Herschel Space Observatory (circles), roughly the same sensitivities of SIRTF and ASTRO-F (triangles), NGST (squares), and ALMA (diamonds).